# How does breakup influence near-barrier fusion of weakly bound light nuclei ?

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# ABSTRACT:

The influence on the fusion process of coupling to collective degrees of freedom has been explored. The significant enhancement of the fusion cross section at sub-barrier energies was understood in terms of the dynamical processes arising from strong couplings to collective inelastic excitations of the target and projectile. However, in the case of reactions where breakup becomes an important process, conflicting model predictions and experimental results have been reported in the literature. Excitation functions for sub- and near-barrier total (complete + incomplete) fusion cross sections have been measured for the $^{6,7}$Li+$^{59}$Co at the VIVITRON facility and at the 8UD PELLETRON tandem facility using standard $\gamma$-ray techniques. The data extend to medium-mass systems previous works exploring the coupling effects in fusion reactions of both lighter and heavier systems. Results of Continuum-Discretized Coupled-Channel (CDCC) calculations indicate a small enhancement of total fusion for the more weakly bound $^{6}$Li at sub-barrier energies, with similar cross sections for both reactions at and above the barrier. A systematic study of $^{4,6}$He induced fusion reactions with the CDCC method is in progress. The understanding of the reaction dynamics involving couplings to the breakup channels requires the explicit measurement of precise elastic scattering data as well as yields leading to the breakup itself. Recent coincidence experiments for $^{6,7}$Li+$^{59}$Co are addressing this issue. The particle identification of the breakup products have been achieved by measuring the three-body final-state correlations.



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# 1 Introduction

The study of fusion reactions in the vicinity of the Coulomb barrier provides a fascinating challenge for theories of quantum tunneling leading to an irreversible complete fusion of the interacting nuclei into the compound nucleus (CN) [1, 2, 3, 4]. A great experimental effort involving both (loosely bound) stable and unstable nuclei has been devoted to investigate the specific role of the breakup channel [4]. The recent availability of light-mass radioactive ion beams such as $^{6}$He [5, 6, 7], $^{11}$Be [8], and $^{17}$F [9], motivated the investigation of fusion reactions involving very weakly bound nuclei around and below the Coulomb barrier.

The fusion probability is sensitive to the internal structure of the interacting ions as well as to the influence of the other competiting mechanisms such as nucleon transfer and/or breakup which are known to affect the fusion features [4]. The fusion cross section enhancement generally observed at sub-barrier energies is understood in terms of dynamical processes arising from couplings to collective inelastic excitations of the target and/or projectile. However, in the case of reactions where at least one of the colliding ions has a sufficient low binding energy so that breakup becomes an important process, conflicting experimental [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16] and theoretical results are reported [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32].

Clearly a full understanding of the effects of breakup on near-barrier fusion requires systematic and detailed measurements covering a wide range of systems and energies. Here we choose to study both the total fusion [33, 34, 35] and breakup [35, 36, 37] of $^{6,7}$Li with the intermediate-mass target $^{59}$Co. Fusion measurements have been performed by detecting characteristic $\gamma$ rays emitted from the resulting evaporation residues [33], which could in principle also allow us to distinguish between the different kind of fusion processes: complete fusion (CF) and incomplete fusion (ICF). CF requires the possibility of fusion through the CN formation containing all the nucleons of both the intact projectile and the target. If only part of the projectile-like fragments may emerge from the interaction region with a compound system being formed then ICF is defined (in this case the breakup process is followed by fusion [11, 18, 22, 26, 33]). Breakup yield measurements have been achieved by measuring the three-body final-state correlations with charged particle techniques [35, 36, 37].

The present work extend the fusion study for medium-mass systems by exploring the coupling effects (hindrance versus enhancement) in the framework of the Continuum-Discretized Coupled-Channel CDCC method [26]. Whereas a small enhancement of total (a sum of CF and ICF cross sections) fusion is observed for the more weakly bound $^{6}$Li at sub-barrier energies, this enhancement is predicted to be much more significant for halo nuclei such as $^{6}$He. The effect disappears above the barrier [33].

In this work we present the fusion data for $^{6,7}$Li+$^{59}$Co in Sec. II analysed by detailed CDCC calculations in Sec. III. Their elastic data as well as the corresponding exclusive light charged particle experiment (which analysis is still in progress) is described in Sec. IV while a summary with very preliminary conclusions and some perspectives using the CDCC approach are given in Sec. V.

# 2 Experimental $\gamma$-ray method and data analysis

The $^{6}Li+^{59}Co$ and $^{7}Li+^{59}Co$ fusion reactions are used to investigate the effect of breakup on the fusion cross section [33, 34, 35, 36, 37]. These fusion-evaporation measurements help to establish the influence of the projectile breakup on the fusion process at near-barrier energies and show how the mass of the target affects the process, as well as the ICF yield. Experiments have been performed either at the Vivitron electrostatic tandem accelerator of the IReS Strasbourg [33] or at the 8UD Pelletron tandem facility of the University of São Paulo [34, 35]. Standard $\gamma$-ray techniques have been used for the Strasbourg measurements: the $\gamma$-ray events were detected with part of the Garel+ spectrometer array [33] configured with 14 Compton-suppressed, high-efficiency Eurogam-type Hp Ge detectors together with one LEPS (Low-energy Photon Spectrometer) detector. The absolute efficiency (for a calibrated $^{60}Co$ source) for Garel+ was 1.2±0.2% and 0.48±0.04% for the São Paulo Ge detector setup. More details of the experimental setup and the analysis procedures are given in Ref. [33].

It is important to notice that the complete data set presented in this work for the $^{6}Li+^{59}Co$ and $^{7}Li+^{59}Co$ fusion reactions using the $\gamma$-ray spectroscopy method is in very good agreement with $^{6,7}Li+^{64}Zn$ data obtained with charged particle techniques [38]. Unfortunately, it has not been possible to clearly resolve the ICF and CF components for the $^{59}Co$ target results [33]. In principle, it should be possible to estimate the ICF contribution by studying the specific population pattern of states in the ER's in the context of statistical-model calculations for these population patterns. Although the current data [33] do not have high-statistics to perform a definite analysis, Signorini *et al.* [39] have been able to perform statistical-model calculations (with the PACE2 code). These imply that $\alpha$ ($t$) ICF components are rather weak. In the following the ER cross sections will be considered to be the total fusion cross sections when compared with the various theoretical calculations [22, 24, 26, 33].

Fig. 1.(a) displays the experimental excitation functions of the total fusion cross sections measured for the two studied reactions. The average fusion excitations functions can be obtained by fitting the data of Fig. 1.(a) can be obtained with the phenomenological one-dimensional barrier penetration model (SBPM) of Wong [40]. The use of this crude parametrization is still justified in the energy region near the Coulomb barrier when inelastic and transfer channel coupling do not affect the total fusion cross section significantly. The results of such SBPM fits are compared for the quantity $\sigma_{fus}\mathrm{E}_{c.m.}$ plotted as a function of the center of mass energy $E_{c.m.}$ in Fig. 1.(b) for the two reactions $^{6}Li+^{59}Co$ (in blue color) and $^{7}Li+^{59}Co$ (in red color). The relevant parameters are the barrier radius $R$, the "curvature" $\hbar\omega$ of the barrier, and the barrier height $\mathrm{V}_B$. For near-barrier energies the three parameters control the position and slope of the curves plotted in Fig. 1.(b). The values of the parameters are found to be consistent with the current systematics [13, 38] with the noticeable exception of the $\hbar\omega$ value being too high (8.1 MeV) for $^{6}Li$. Although SBPM fitting can still be done

even if inelastic and/or transfers are important, this anomalous value may give some indication that the direct breakup/scattering process might have a significant influence on the total fusion cross section.

In order to better isolate the effects of possible couplings, it is important to use a clear reference when an enhancement and/or a suppression is defined. Therefore the ratio R = $\sigma(^6\text{Li})/\sigma(^7\text{Li})$ between the total fusion cross sections for $^6$Li and $^7$Li induced reactions shown in Fig. 1.(a) is calculated for this purpose. It should be noted that the $^7$Li induced reaction is used as reference due to its higher binding energy (2.47 MeV) when compared to 1.475 MeV for $^6$Li. This ratio is displayed in Fig. 2 as a function of $E_{c.m.}$ and compared to CC calculations [22, 24] discussed in the next Section.

# 3 Coupled-Channels calculations

Since the coupling of the relative motion between colliding nuclei to the inelastic (and transfer) channels is known to enhance the fusion cross section at sub-barrier energies [19], CC effects are usually taken into account in the theoretical descriptions of the fusion process. The question of whether the breakup process may strongly influences the fusion processes (i.e. as a sub-barrier enhancement) remains open. Therefore we have chosen to apply two different CC approaches [22, 24] to the $^{6}$Li+$^{59}$Co and $^{7}$Li+$^{59}$Co fusion reactions presented in this work. The solid curve in Fig. 2 shows the ratio calculated the model of Wong [40] using independent fits of two SBPM parametrizations shown in Fig. 1.(b). If the only difference between the two lithium isotopes was the $A^{1/3}$ dependence of the radius, one would expect a simple shift in energy due to the corresponding difference in barrier heights. This shift should be around 0.14 MeV and the dotted curve gives the resulting ratio in Fig. 2; the latter clearly goes in a direction opposite to the experimental data at sub-barrier energies.

The other curves plotted in Fig. 2 correspond to two CC calculations [22, 33] with and without reorientation effects (microscopic differences in the structure of the two Li isotopes lead to different reorientation terms in the channel couplings) performed by using the CCFULL code [41]. This code solves the Schrödinger equation and the coupled equations exactly, making only the iso-centrifugal approximation. The fusion cross sections are calculated using an incoming wave boundary condition and taking a Woods-Saxon form for the nuclear potential [42]. The potential parameters were taken to be identical for both projectiles: the depth $V_0$ = 74.0 MeV, the radius parameter $r_0$ = 1.05 fm, and the diffuseness parameter $a$ = 0.63 fm. This value is very close to the predictions using the Woods-Saxon parametrization of the Akyüz-Winther potential [42] which gives $a$ = 0.62 fm and $a$ = 0.63 fm, respectively, for the $^{6}$Li and $^{7}$Li induced reactions. From the inspection of Fig. 2 no suppression is observed at energies above the barrier (one should point out that the experimental data presented in Ref. [33] do not allow us to distinguish between CF and ICF components) and a sub-barrier enhancement is observed for $^{6}$Li. It is clear, however, that all the details of the data, particularly at sub-barrier energies, are not reproduced by the present CC calculations. More realistic CC calculations, taking into account the interplay between projectile breakup and fusion in the framework of the CDCC approach [26], have been undertaken and presented in Fig. 1.

A traditional approach to discuss the sub-barrier fusion reaction induced by weakly bound nuclei is to solve the CC equations by discretizing in energy the continuum states in the projectile nucleus. Here the CC calculations were performed by using the so-called Continuum-Discretized Coupled-Channel (CDCC) method [24]. All details concerning the breakup space (number of partial waves, maximum continuum energy cuttof ...) for $^{6}$Li to obtain converged total fusion cross sections have been given elsewhere Refs. [24, 26] (in particular in Table I of [26]), and the CDCC scheme is available in a general CC computer code FRESCO [43]. We would like to stress that in the chosen calculations the imaginary parts of the off-diagonal couplings have been neglected, while the diagonal couplings include imaginary parts. We have used short-range imaginary fusion potentials for each fragment separately. This is equivalent to the use of incoming boundary conditions in CCFULL calculations and guarantees that at least one of the fragments of the projectile is captured.

The measured excitation functions that were reported previously in Refs. [33, 34, 35, 36, 37] are here presented in Fig. 1 (open squares and open circles) with the comparison with predictions (labelled 'theory' with full triangles and full squares) of CDCC calculations for both the $^{7}$Li+$^{59}$Co and $^{6}$Li+$^{59}$Co reactions, respectively. It is shown that the CDCC calculations of Fig. 3 predict the same significant enhancement of $^{6}$Li (with smaller $\alpha$-breakup threshold than for $^{7}$Li) fusion cross section. This is due to the fact that breakup enhances the total fusion cross section just around the Coulomb barrier, whereas it hardly affects (an enhancement of less then $\approx$ 2%) the fusion at energies well above the barrier, as expected.

The $^{6}$He+$^{59}$Co case is much more complicated since $^{6}$He breaks into three fragments instead of two, and the CDCC method has not yet been developed for two-nucleon halo nuclei [24]. We have used the same model as for $^{6}$Li+$^{59}$Co case described above. Hence for the $^{6}$He+$^{59}$Co reaction we assume a two-body cluster structure of $^{6}$He = $^{4}$He + 2n. The potential between the $\alpha$ particle and the $^{59}$Co target appears on Table 1 of Ref. [26]. Similarly to our previous work [26], the potentials between the fragments and the $^{59}$Co target are those obtained with the global Broglia-Winther Woods-Saxon parametrization given in Ref. [42] for the Christensen and Winther potential [44] (the numerical values are: $V_o$=-16.89 MeV, $r_o$=1.09 fm and a=0.63 fm). For the $\alpha$-2n binding potential ($0^+$ g.s) we have used the following Woods-Saxon potential: $V_o$= -40.796 MeV, $r_o$=1.896 fm and a=0.3 fm. The g.s. binding potential of the $\alpha$ particle and the dineutron provides a 2s bound state of about -0.975 MeV. The binding potential of the $2^+$ resonant state has also a Woods-Saxon form with the following parameters: $V_o$=-35.137 MeV, $r_o$=1.896 fm, a=0.3 fm. With this potential the energy of the $2^+$ resonant state is 0.83MeV and its width is 0.075 MeV. To obtain converged (within a 5%) total fusion cross section we have included: (i) partial waves for $\alpha$-2n relative motion up to f-waves ($l = 3$), (ii) the $^{6}$He fragment-target potential multipoles up to the octupole term, and (iii) the maximum of the continuum energy is 8 MeV. All resonant and non-resonant continuum couplings including continuum-continuum couplings were included in the calculation.

Preliminary CDCC calculations using the set of parameters given for the $^{6}$He+ $^{59}$Co reaction in the previous paragraph are displayed in Figs. 4 and 5. The present calculations do not include neither target excitations nor transfer channnels. However with crude estimations as those performed for the $^{6}$Li+$^{59}$Co reaction [26] the effect is found to be very small. In Fig. 4 we compare the total fusion excitation functions of the two

$^{6}$He+$^{59}$Co (CDCC calculations) and $^{6}$Li+$^{59}$Co (experimental data of Ref. [33]) reactions. For the $^{6}$He reaction, the incident energy is also normalized with the Coulomb barrier $V_B$ of the bare potential. The first calculation (dashed line) only include the reorientation couplings in fusion without breakup. All contiunum and reorientation couplings are included in fusion with breakup (solid curve). We can observe that both calculated curves (with and without breakup) give much larger total fusion cross section for $^{6}$He as compared to $^{6}$Li. We can also observe that the inclusion of the couplings to the breakup channels notably increases the total fusion cross section for the whole energy range. The same conclusions are reached when $^{6}$He+$^{59}$Co (CDCC calculations) is compared to $^{4}$He+$^{59}$Co (here the CDCC calculations are fitting the data of Ref. [53] remarkably well) in Fig. 5.

In contrast to stable weakly bound nuclei such as $^{7}$Li and $^{6}$Li, the questions in the theory of a halo system such as $^{6}$He, its breakup (and in the breakup of many-body projectiles generally), and its CF and ICF components will need the knowledge not just of those integrated cross sections, but the phase space distributions of the surviving fragment(s). Therefore, future very exclusive experiments will have to determine very precisely the angular correlations of the light charged particles and the individual neutrons. In the next Section we present a first attempt with the stable loosely bound projectiles $^{6,7}$Li and the results of a new $\alpha$-$d$ and $\alpha$-$t$ coincidence experiment performed with the $^{59}$Co target.

# 4 Elastic data and coincidence measurements

In complete CC calculations, such as the ones performed with the CDCC formalism [22, 24, 26], a final tuning for the coupling of the breakup channel, as well as the correct description of the reaction dynamics, will require the explicit measurement of precise elastic data as well as yields leading to breakup itself. Detailed elastic and breakup measurements are still very scarce and limited to heavy targets [45, 46, 47]. This has motivated us to perform exclusive experiments, that include also detailed measurements of elastic scattering and the transfer/breakup channels, have been undertaken systematically at the University of São Paulo Pelletron Laboratory to investigate the $^{6}$Li+$^{12}$C,$^{59}$Co,$^{115}$In reactions and for the $^{7}$Li+$^{12}$C,$^{59}$Co,$^{115}$In reactions [36, 37].

In the following we will discuss only the results of the preliminary analysis that has been accomplished for the $^{59}$Co target (experimental data for the $^{12}$C and $^{111}$In targets are partially presented elsewhere [36, 37]). Fig. 6 displays the angular distributions of the elastic scattering data for both the $^{7}$Li+$^{59}$Co (left side) and the $^{6}$Li+$^{59}$Co (right side) systems measured at four different bombarding energies $E_{lab}$ = 12, 18, 26, and 30 MeV close to the Coulomb barrier. The analysis of the elastic scattering data has been performed by following the new potential systematics of Gasques *et al.* [48]. According to a Hauser-Feshbach calculation the possible contribution of the compound-elastic decay has been estimated to be negligible for the 8 measured elastic angular distributions dispayed in Fig. 6. It is interesting to note that the potential required for the Optical Model (OM) calculations performed to reproduce the elastic scattering data of Fig. 6 is very similar to the $^{6}$Li+$^{64}$Zn and $^{7}$Li+$^{64}$Zn OM potentials of Ref. [38]. It qualitatively resembles the effective potentials introduced either in the CDCC analysis [26] of the fusion cross sections [33] (presented in Fig. 1) or in the CCFULL analysis [33] of the yield ratios shown in Fig. 2. As a consequence the total reaction cross sections extracted from this OM analysis are also well accounted for by the two CC approaches. For instance the ratios $R = \sigma(^{6}\mathrm{Li})/\sigma(^{7}\mathrm{Li})$ between the total reaction cross sections for $^{6}$Li and $^{7}$Li induced reactions (R = 1.52 for $E_{c.m.}$ = 11.0 MeV and 0.96 and 0.94 for $E_{c.m.}$ = 16.5 MeV and 23.5 MeV, respectively) are comparable to the ratio R shown in Fig. 2 for the total fusion cross sections.

Fourteen triple telescopes [49] were used to provide a simultaneous detection of light- and heavy-ion products. A more precise identification of the breakup products has been achieved by measuring the three-body final-state correlations [36]. Coincidence data allow the identification of the process Q-value in order to gate exclusively on the projectile breakup channel. Furthermore, the system excitation energy as well as the projectile fragment relative energy are used to identify the exit channel without ambiguity. Based on those filters (see Fig. 7), angular correlations (such as the ones shown in Fig. 8) can be obtained in order to identify the different processes (CF, ICF and breakup) involved in the reaction.

Fig. 7 shows one of the typical bidimensional energy correlation plot $E_{\alpha d}$ versus $E_{\alpha}$ that has been measured at $E_{lab}$ = 26 MeV for the $^{6}$Li+$^{59}$Co system. The line represents the loci for events leaving $^{59}$Co in the ground state and the first resonant state of $^{6}$Li at $E^{*}$ = 2.186 MeV ($J^{\pi}$ = $3^{+}$). This is complemented by measurements of relative energy of the fragments using different rest frame references (like target, projectile, target + fragment) in order to disentangle the different contributions of breakup, ICF and/or transfer-reemission processes. The obtained exclusive data can be compared to three-body kinematics calculations [36].

The relative energy between $\alpha$-$d$ for the $^{6}$Li breakup on a $^{59}$Co target is deduced from the angular interval where the relative energy is predicted to be constant by the three-body kinematics. Fig. 8(a) and Fig. 8(b) display the corresponding angular correlations of the $\alpha$-$d$ and $\alpha$-$t$ coincidences measured at $E_{lab}$ = 22 MeV for the $^{59}$Co($^{6}$Li,$\alpha$ $d$) and $^{59}$Co($^{7}$Li,$\alpha$ $t$) reactions, respectively. As expected from the low $\alpha$-$d$ breakup threshold at 1.475 MeV of $^{6}$Li the coincident yields for the $^{6}$Li induced reaction are much higher than for $^{7}$Li. The rather small $\alpha$-$t$ yields in $^{7}$Li+$^{59}$Co are comparable with the previous breakup study of the $^{7}$Li+$^{56}$Fe [50]. The fact that the angular correlations of Figs. 8 are not regular indicates the occurence of several contributions. The $\alpha$ - $d$ coincidence yields are not negligible out of the three-body breakup region due the occurence of other mechanisms which are mixed. Work is in progress to distinguish more quantatively breakup from ICF and/or transfer processes.

This procedure of unfolding several different light-particle emission processes has not been exploited so far in the literature. Similar data were taken for the $^{6,7}$Li+$^{12}$C and $^{6,7}$Li+$^{112}$In collisions [36, 37]. A theoretical analysis in the framework of the CDCC formalism [26] is underway.

# 5 Summary and conclusions

Measurements of the excitation functions for sub- and near-barrier total fusion (complete fusion + incomplete fusion) [33] have been presented for the stable, weakly bound projectiles $^6$Li and $^7$Li on the medium-mass $^{59}$Co target. Evaporation residues were identified by their characteristic $\gamma$ rays and the corresponding yields measured using the $\gamma$-ray spectroscopy method. Above the Coulomb barrier, the fusion yields are found to be very close for both systems, in agreement with CDCC calculations [26]. The results are consistent with there being no significant fusion hindrance caused by breakup effects. The absence of breakup suppression of the total fusion cross sections above the barrier appears to be a common feature of $^{6,7}$Li induced reactions, regardless of target mass. An enhanced yield is observed below the Coulomb barrier for the loosely bound $^6$Li projectile as compared to that found for the more tightly bound $^7$Li.

Subsequent experiments using charged particle spectroscopy techniques have been carried out to measure precise elastic angular distributions as well as the light-particle breakup channels for both $^{6,7}$Li+$^{59}$Co reactions. These measurements are essential to determine the coupling strength to the breakup channel that will be introduced in full CC calculations to be performed in the framework of the CDCC formalism [26]. The total reaction cross sections extracted from the OM analysis of the elastic scattering data confirms the enhanced fusion yield observed for $^6$Li at sub-barrier energies.

Both halo and cluster weakly bound nuclei, with well-defined breakup and fusion modes, are good test-benches for theories of breakup and fusion. A more complete theoretical model of few-body dynamics that is able to distinguish CF from ICF will need to follow correlations after breakup. The new $\alpha$-$t$ and $\alpha$-$d$ correlation data presented in this work for the $^6$Li+$^{59}$Co and $^7$Li+$^{59}$Co reactions (and the corresponding data for the $^6$Li+$^{12}$C,$^{111}$In and $^7$Li+$^{12}$C,$^{111}$In reactions [36, 37]) constitute a first attempt with stable weakly bound projectiles. The CDCC method [26], which is shown here to be very succesfull for fusion, will be used to provide the complete theoretical description of all competing processes (total fusion, elastic scattering, transfer and breakup) in a consistent way.

Finally a systematic study of $^{4,6}$He induced fusion reactions with the CDCC method [26] will be undertaken. However up to now only very scarce studies with $^6$He projectiles are presently available [5, 6, 7, 16, 51, 52]. Data from SPIRAL and Louvain-la-Neuve have recently been published for $^6$He+$^{63,65}$Cu [51] and $^6$He+$^{64}$Zn [52] and very preliminary results of our systematic CDCC analysis show that for $^6$He+$^{59}$Co considerable enhancement of the sub-barrier fusion cross sections is predicted as compared to measured fusion yields for both the $^6$Li+$^{59}$Co [33] and $^4$He+$^{59}$Co [53] systems. A new experimental programme with SPIRAL beams and medium-mass targets is underway at GANIL within the forthcoming years.

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# FIGURES

Figure 1 (a): Energy dependence of the total fusion (CF + ICF) cross sections measured for $^{6}$Li+$^{59}$Co (open circles) and $^{7}$Li+$^{59}$Co (open squares) reactions [33]. The corresponding theoretical values (respectively full squares and full triangles) are obtained with the CDCC method [26]. The arrows indicate the positions of the respective Coulomb barriers of the effective potentials [42, 44].

Figure 1 (b): Energy dependence of the total fusion (CF + ICF) cross sections multiplied by $E_{c.m.}$ (in MeV.mb) for $^{6}$Li+$^{59}$Co (open circles) and $^{7}$Li+$^{59}$Co (open circles) reactions. The corresponding theoretical values (respectively in blue and in red) are obtained by fitting the data with the SBPM model of Wong [40]. The values of the relevant SBPM parameters given in the figure are discussed in the text.

Figure 2: Energy dependence of the ratio of the total (CF + ICF) fusion cross sections for the $^{6}$Li+$^{59}$Co and $^{7}$Li+$^{59}$Co reactions [33]. Error bars reflect the large systematic errors. The solid and dashed curves correspond to SBPM [40] fits of the ratios as explained in the text. The dotted curves correspond to two uncoupled CCFULL calculations [41] with and without reorientation effects, whereas the dot-dashed curve is the result of CCFULL calculations including the coupling to the first excited state.

Figure 3: Energy dependence of the total fusion (CF + ICF) cross sections calculated with the CDCC method [26] for $^{6}$Li+$^{59}$Co (full dots) and $^{7}$Li+$^{59}$Co (full triangles), which are normalized with the CDCC cross sections in the absence of couplings to breakup channels. For each reaction, the incident energy is normalized with the Coulomb barrier of the effective potentials [42, 44]. The calculated CDCC values are connected with curves to guide the eye. See text for further details.

Figure 4: Energy dependence of the total fusion (CF + ICF) cross sections for the $^{6}$He+$^{59}$Co reaction obtained with the CDCC method [26]. The solid and dashed curves corresponds respectively to CDCC with or without continuum couplings. The experimental total fusion cross sections for the $^{6}$Li+$^{59}$Co reaction [33] is given for the sake of comparison. For each reaction, the incident energy is normalized with the Coulomb barrier of the effective potentials [42, 44].

Figure 5: Same as Fig. 4. The $^{6}$He+$^{59}$Co excitation function is compared with the CDCC calculations [26] for the $^{4}$He+$^{59}$Co total fusion cross sections which fit well the experimental CF data from Ref. [53].

Figure 6: Angular distributions of the elastic scattering for the $^{6}$Li+$^{59}$Co (right panel) and $^{7}$Li+$^{59}$Co (left panel) reactions, repectively, measured at the four indicated nera-barrier energies. The solid lines represent OM predictions with the starting parameter set given in the systematic study proposed in Ref. [48] and discussed in detail in the text. The compound-elastic contributions has not been taken into account.

Figure 7: Bidimensional $E_{\alpha d}$ versus $E_{\alpha}$ energy correlation plot measured at $E_{lab} = 26$ MeV for the $^{6}$Li+$^{59}$Co reaction at the indicated correlation angles.

Figure 8: (a) Experimental $\alpha$ - $d$ and $\alpha$ - $t$ angular correlations respectively measured at $E_{lab} = 22$ MeV for the $^{6}$Li+$^{59}$Co reaction (upper panel); (b) same as (a) but for the $^{7}$Li+$^{59}$Co reaction (lower panel).